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Substantiation of the narrow-jet plasma technology for finishing cutting of steel sheets

S V Anakhov¹, N B Pugacheva², T M Bykova², B N Guzanov¹, A V Matushkin³
and Y A Pykin³

¹ State Vocational Professional University, 11 Mashinostroiteley St., Ekaterinburg, 11620012, Russia

² Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, 34 Komsomolskaya St., 620049, Ekaterinburg, Russia,

³ B.N. Yeltsin Ural Federal University, 19 Mira St., Ekaterinburg, 620002, Russia

E-mail: nat@imach.uran.ru

Abstract. The paper presents a study of the effect of the PMVR-5.2 plasma torch inclination angle on the cut surface profile, the structure and hardness of the material of the edge on 10 mm thick 09G2S steel plates. The plasma torch implements the narrow-jet technology. The heat-affected zones prove to have a gradient structure. When cutting is performed at an angle of 30°, there appear ~500 µm thick edges with a 15 to 30 µm thick surface zone of structureless martensite having a microhardness of 900 HV 0.025 and a zone of fine-lamellar pearlite with a hardness of 350 HV 1. This requires mechanical removal of a 40 µm thick layer from the cut surface before subsequent welding. When the plasma torch is inclined at an angle of 90°, the quality of the edge material requires no mechanical removal of the heat-affected zone for subsequent welding.

1. Introduction

Plasma cutting of metal is currently one of the most popular technologies in metallurgy and mechanical engineering. Today, there is a wide choice of metal-cutting plasma torches of various functional purposes and designs, of both domestic and foreign production. A line of research in plasma technologies is their safe application. In most cases, the use of plasma torches requires monitoring and ensuring a safe level of noise emission, gas-aerosol pollution, heat, light, and electromagnetic loads. This can be achieved in the following ways: designing plasma torches with a reduced negative effect on the staff, using protective means and devices, and regulating the operating conditions under increased harmful effects. Note the actual absence of narrow-jet plasma torches from the domestic market. The narrow-jet plasma technology [1] significantly exceeds the conventional methods of plasma cutting of thin and medium-thickness metals in terms of efficiency and power consumption, and it is comparable with laser cutting of metals in terms of the width and quality of the cut [2].

Unfortunately, despite the existing theoretical developments of these technologies in Russian engineering [3], products of only foreign manufacturers (Hypertherm, Kjellberg, Messer Griesheim) are currently available on the market. In order to create a plasma torch implementing the narrow-jet technology, a multiannual experience in research and design of plasma torches for various applications was used [4]. As a result, several modifications of the PMVR-5 narrow-jet plasma torch with an upgraded system of gas vortex stabilization and plasma jet compression were developed. This system increases the efficiency of heat input and enhances the quality of the metal in the cutting area. The



quality of subsequent welding is affected by the thickness of the heat-affected zone (HAZ) after cutting, its microstructure and hardness, as well as by the cut surface roughness, the characteristics being regulated by GOST 14792-80.

The aim of this paper is to study the roughness, microstructure, and microhardness of the edge surface, which characterize the quality of structural low-alloy steel cuts made with the use of the PMVR-5.2 plasma torch.

2. Materials and research methods

Plasma cutting was performed with the use of a PMVR-5.2 plasma torch (Fig. 1a), produced by Poligon LLC, at different angles of plasma torch inclination, as shown in Fig. 1b. The design of the gas-air path (GAP) of the PMVR-5.2 plasma torch is based on the principle of stepwise equalization of plasma forming gas (PFG) velocity across the duct section (i.e., the gas comes from duct 1 to duct 2, then from 2 to 4, etc.). The main swirler is the final element in this chain. The design feature of this swirler is that the PFG flow passing through the swirler is supplied tangentially to the cathode surface in the plane perpendicular to the cathode. A commercially available A-141 cathode with a series of 1.4 to 1.8 mm outlet diameter nozzles is used in the plasma torch design. Due to the concepts used in the design of the gas-air path of the plasma torch and its cooling system, it was possible to increase by 15–20% the maximum permissible cutting current for the A-141 cathode and nozzle used in the design. The cutting technology was chosen in view of the possible further use of thin-sheet steel (up to 20–25 mm) for the production of butt welds (plasma torch kept at an angle of 90°), or for the welding of medium-thickness (25 to 40 mm) steels (edge preparation with a plasma torch inclined at an angle of 30°), Fig. 1b. The cutting process conditions are given in Table 1.

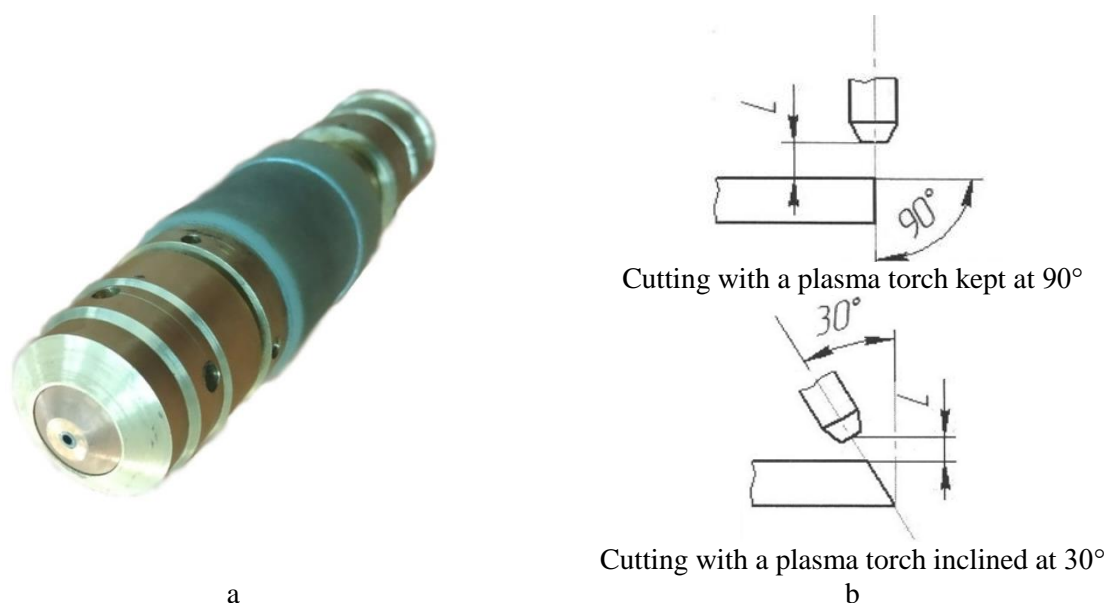


Figure 1. A PMVR-5.2 plasma torch (a); the cutting schemes (b).

Table 1. The cutting conditions

| Inclination angle | Arc current [A] | Arc voltage [V] | Cutting speed [m/min] | Nozzle diameter [mm] | Distance from the nozzle section L [mm] | Plasma-forming gas pressure [MPa] |
|-------------------|-----------------|-----------------|-----------------------|----------------------|---|-----------------------------------|
| 30° | 115 | 200 | 1.25 | 1.7 | 5 | 0.5 |
| 90° | 88 | 180 | 0.75 | 1.7 | 5 | 0.5 |

Plates of the 09G2S sheet steel, which is one of the main materials in the production of welded blanks, were subjected to plasma cutting. The plate thickness was 10 mm. It should be noted that 10 mm thick metal is cut by a plasma torch with upgraded individual gas vortex stabilization and plasma jet compression at a much higher speed (0.75 to 1.1 m/min) than by conventional single-tube gas plasma torches (0.54 m/min). As a result, in addition to the expected improvement of the cutting quality owing to reduced heat input into the cutting zone, a significant increase in productivity, energy efficiency, and process safety is achieved [5].

The sample surface profile after plasma cutting was examined with a Veeco optical interferometer in the center of the cut. The metallographic structural analysis of the samples etched in a reagent based on a 4% solution of nitric acid in ethyl alcohol was performed on a Neophot 21 microscope at a magnification of 100 \times . The steel microstructure was identified by comparison with the reference scales according to GOST 8233-56. The hardness of the samples was measured on a Leica device under loads of 0.245 (only the near-surface layer with a thickness of at most 20 μm) and 9.8 N on the indenter. The imprinting scheme is shown in Fig. 2.

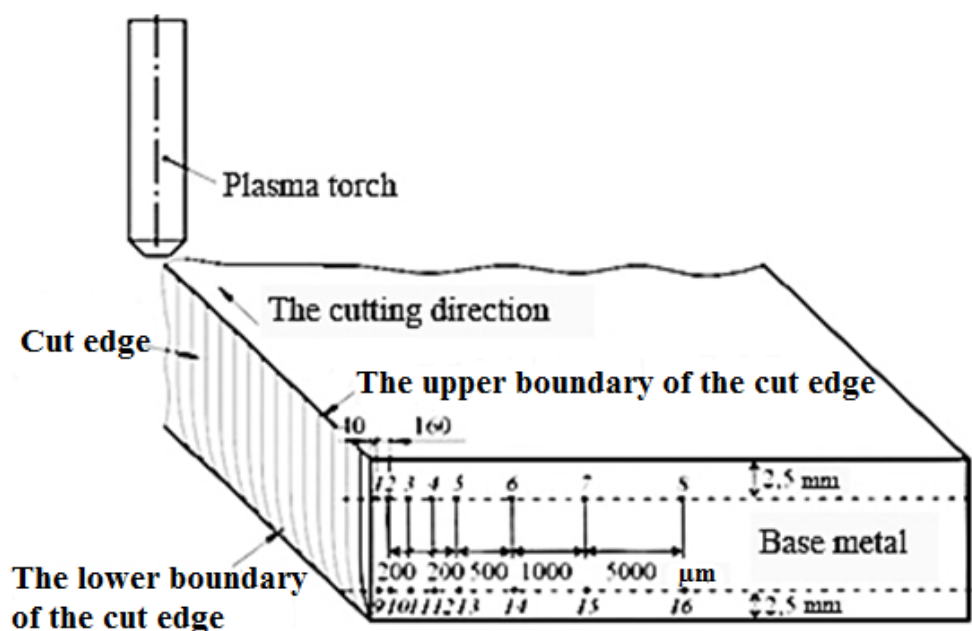


Figure 2. Cut edge hardness measurement scheme.

3. Results and discussion

The examination of the cut surface (Fig. 3) has shown that the average roughness value ranges between 7 and 9 μm (Table 2), and this corresponds to the 1st class of quality according to GOST 14792-80. The maximum surface roughness values are also within the permissible limits (at most 50 μm) for the 1st class of quality.

The base metal of the samples, which did not undergo heating and structural changes in the process of cutting, has a typical ferrite-pearlite structure, the perlite/ferrite (P/F) ratio being 20/80 on scale 7 according to GOST 8233-56 (Fig. 4). During plasma cutting, the metal melts in the zone of plasma jet action, whereby the plate is divided into two fragments. Near the cut surfaces, the steel is heated to different temperatures depending on the length deep into the plate. The material of the edge is the heat affected zone structurally consisting of 3 subzones. The first near-surface subzone of the maximum steel overheating consists of structureless martensite (the bright stripe in Fig. 4a) with a hardness of 900 HV 0.025, where the cooling rate has maximum values due to the summation of surface cooling

and heat dissipation through the plate material. The thickness of the martensitic zone ranges from 15 to 30 μm at a plasma torch inclination angle of 30° and does not exceed 5 μm at a cutting angle of 90° . The second subzone consists of pearlite, whose dispersion varies with the plasma torch inclination angle. At an angle of 30° , 5-grade fine lamellar pearlite is formed on scale 1 according to GOST 8233-56, with an interlamellar distance of 0.80 μm (Fig. 4a), the subzone width being 185 μm . At a cutting angle of 90° , 6-grade medium lamellar pearlite with an interlamellar distance of 1.00 μm is formed, the subzone width being 100 μm (Fig. 4b).

The third subzone consists of pearlite and ferritic grains. At an inclination angle of 30° , P/F=65/35, the subzone width being 280 μm . When the angle is 90° , P/F=50/50, the subzone width being 250 μm . The total HAZ thickness for the plates cut at an angle of 30° is about 375 μm , and it is 500 μm for the plates cut at an angle of 90° . This corresponds to the 2nd class of quality according to GOST 14792-80.

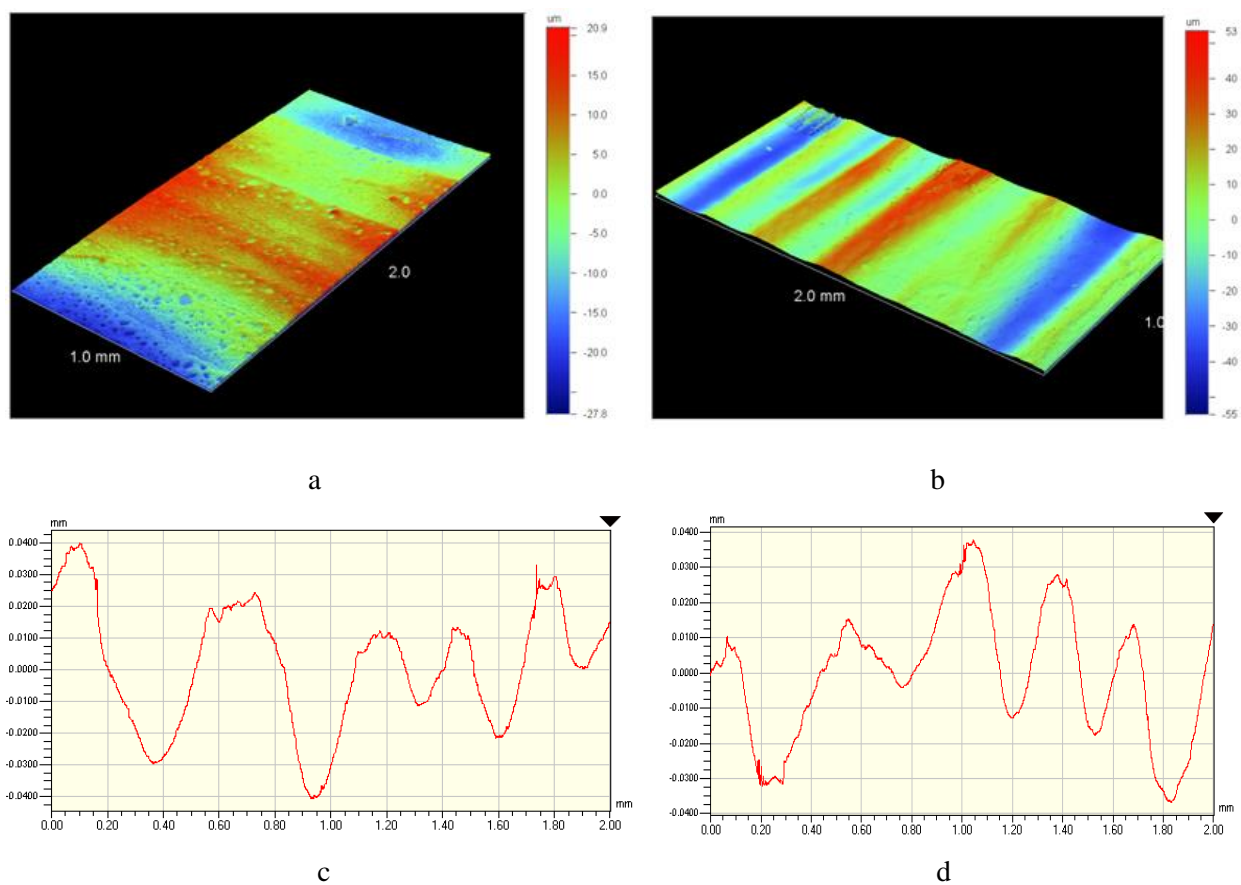


Figure 3. Cutting surface profile (a, b) and profilograms (c, d); a, c – plasma torch inclined at 30° ; b, d – plasma torch kept at 90° .

Table 2. The results of surface roughness examination

| Plasma torch inclination angle | Average surface roughness (Ra) [μm] | Maximum profile height (Rt) [μm] |
|--------------------------------|--|---|
| 30° | 7.3 | 38.7 |
| 90° | 8.0 | 48.2 |

A large proportion of ferrite in the HAZ structure for the plates cut at a plasma torch inclination angle of 90° causes smaller changes in hardness, as shown in Table 3 and Fig. 5. According to the

requirements of the STO Gazprom 2-2.4-083 application standard, the HAZ hardness values after plasma cutting must not exceed 300 HV. This requirement is fully met at a cutting angle of 90° , and this allows one to avoid additional machining of the cut surface during subsequent welding of the cut plates. Cutting at an angle of 30° requires the removal of a $40\ \mu\text{m}$ thick surface layer before welding.

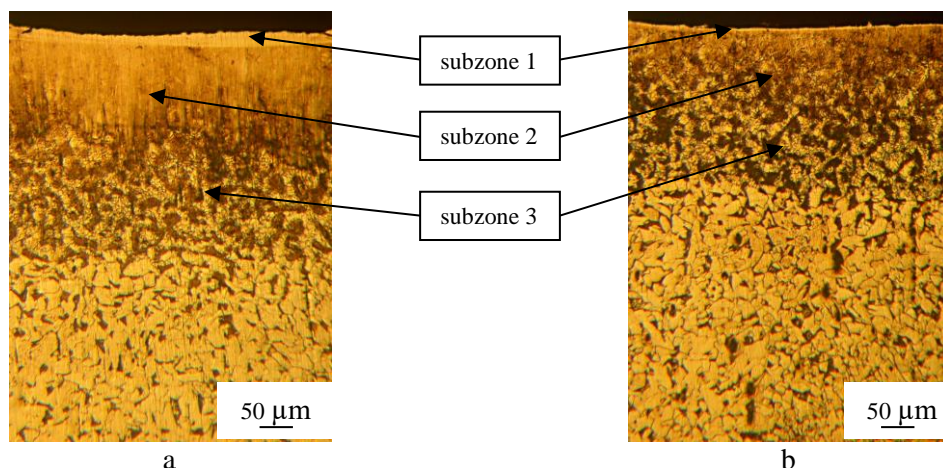


Figure 4. The structure of the sample surface in the cutting area: a – plasma torch inclined at 30° ; b – plasma torch kept at 90° .

Table 3. Hardness variation in the surface layer on the side of the cut

| Distance from the surface [μm] | Plasma torch inclined at 30° | | | Plasma torch kept at 90° | | |
|---|-------------------------------------|--------|--------|---------------------------------|--------|--------|
| | Input | Center | Output | Input | Center | Output |
| 40 | 347 | 356 | 356 | 311 | 273 | 263 |
| 160 | 261 | 289 | 289 | 314 | 262 | 269 |
| 200 | 235 | 274 | 231 | 278 | 227 | 258 |
| 200 | 211 | 217 | 198 | 226 | 216 | 236 |
| 200 | 203 | 203 | 196 | 198 | 199 | 230 |
| 500 | 195 | 189 | 178 | 190 | 217 | 203 |
| 1000 | 180 | 179 | 174 | 174 | 180 | 194 |
| 5000 | 170 | 168 | 162 | 167 | 176 | 175 |

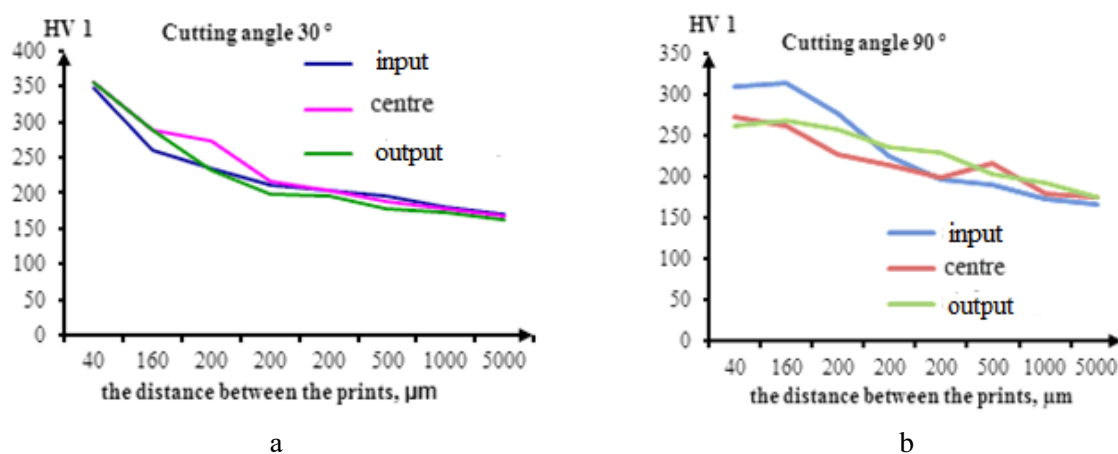


Figure 5. Hardness distribution in the sample: a – plasma torch inclined at 30° , b – plasma torch kept at 90° .

4. Conclusion

The use of the new plasma torch allows one to produce edges with medium (7 to 9 μm) and maximum (48 μm) surface roughness, corresponding to quality class 1 according to GOST 14792-80, on 09G2S steel plates. The heat-affected zones have a gradient structure with a proportion of pearlite smoothly increasing to 100% of its content near the cutting surface. High cooling rates during cutting at an angle of 30° induce structureless martensite on the surface, the thickness of this zone not exceeding 30 μm .

The requirement of the STO Gazprom 2-2.4-083 application standard for hardness values (≤ 300 HV) is fully feasible for plasma cutting of 09G2S steel plates at a plasma torch inclination angle of 90° ; this enables edges on sheet steel to be used for welding without removing heat-affected zones. After edge preparation by cutting at an angle of 30° , typical for welding of medium-thickness steels, it is required to remove mechanically the surface layer no thicker than 40 μm .

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